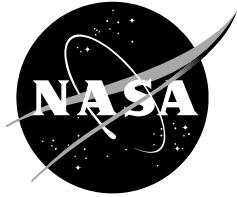


NASA/CR-2010-216287



Verify MesoNAM Performance

William H. Bauman III

ENSCO, Inc., Cocoa Beach, Florida

NASA Applied Meteorology Unit, Kennedy Space Center, Florida

September 2010

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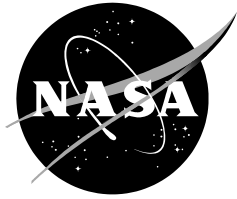
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*William H. Bauman III
ENSCO, Inc., Cocoa Beach, Florida
NASA Applied Meteorology Unit, Kennedy Space Center, Florida*

National Aeronautics and
Space Administration

*Kennedy Space Center
Kennedy Space Center, FL 32899-0001*

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Available from:

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Executive Summary

The 45th Weather Squadron (45 WS) Launch Weather Officers (LWOs) use the 12-km resolution North American Mesoscale (NAM) model (MesoNAM) forecasts extensively to support launch weather operations. However, the actual performance of the model at Kennedy Space Center (KSC) and Cape Canaveral Air Force Station (CCAFS) has not been measured objectively. In order to have tangible evidence of model performance, the 45 WS tasked the Applied Meteorology Unit (AMU) to conduct a detailed statistical analysis of model output compared to observed values. The analysis compared the MesoNAM forecast winds, temperature and dew point to the observed values from the sensors on specified KSC/CCAFS wind towers.

The AMU calculated the following statistics to verify the performance of the model:

- Bias (mean difference),
- Standard deviation of Bias,
- Root Mean Square Error (RMSE), and
- Hypothesis test for Bias = 0.

The AMU calculated the verification statistics once the files were properly formatted and stratified. First the difference between all hourly model forecasts and tower observations was calculated and then the mean monthly bias, the standard deviation of the mean monthly bias and then the RMSE. Finally, the hypothesis zero test was applied to the mean monthly bias statistics.

The model's performance statistics were calculated for each wind tower based on sensor height and model initialization time. The data were stratified by month and onshore/offshore wind direction based on the orientation of the coastline to each tower's location prior to the statistics calculations.

The 45 WS requested the AMU only calculate statistics for the current MesoNAM which became operational in mid-August 2006 and was based on the Weather Research and Forecasting model. Therefore the period of record for the data used in this task began with the first full month of data, September 2006, through May 2010.

The model performance indicated:

- The accuracy decreased as the forecast valid time from the model initialization increased,
- There was a diurnal signal in temperature with a cool bias during the late night and a warm bias during the afternoon,
- There was a diurnal signal in dew point temperature with a low bias during the afternoon and a high bias during the late night, and
- The model parameters at each vertical level most closely matched the observed parameters at heights closest to those vertical levels.

The AMU developed a graphical user interface (GUI) that consists of a multi-level drop-down menu written in JavaScript embedded within Hyper-Text Markup Language code that can be used with most popular web browsers. This GUI allows the LWO to easily and efficiently navigate among the charts and spreadsheet files.

The objective statistics provide the forecasters knowledge of the model's strengths and weaknesses and the GUI allows quick access to the data which will result in improved forecasts for operations.

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1. Introduction

The 45th Weather Squadron (45 WS) Launch Weather Officers (LWOs) use the 12-km resolution North American Mesoscale (NAM) model (MesoNAM) text and graphical product forecasts extensively to support launch weather operations. However, the actual performance of the model at Kennedy Space Center (KSC) and Cape Canaveral Air Force Station (CCAFS) has not been measured objectively. In order to have tangible evidence of model performance, the 45 WS tasked the Applied Meteorology Unit (AMU; Bauman et al. 2004) to conduct a detailed statistical analysis of model output compared to observed values.

The model products are provided to the 45 WS by ACTA, Inc. and include hourly forecasts from 0 to 84 hours based on model initialization times of 00, 06, 12 and 18 UTC. The objective analysis compared the MesoNAM forecast winds, temperature (T) and dew point (T_d), as well as the changes in these parameters over time, to the observed values from the sensors in the KSC/CCAFS wind tower network shown in Table 1. The LWOs support launch and landing activities using the sensors in the column labeled “*Required Sensor Heights*”. The other sensors present on the towers are shown in the column labeled “*Additional Sensor Heights*” and were included in this work for completeness. The objective statistics calculated will give the LWOs knowledge of the model’s strengths and weaknesses based on the observations at individual wind towers, which will result in improved forecasts for operations.

Table 1. Towers, launch activities and sensor heights at KSC and CCAFS used in the objective analysis to verify the MesoNAM forecasts.			
<i>Tower Number</i>	<i>Supported Activity and Facility</i>	<i>Required Sensor Heights</i>	<i>Additional Sensor Heights</i>
002	Delta II (LC-17)	6 ft, 54 ft, 90 ft	145 ft, 204 ft
006	Delta IV (LC-37)/Falcon 9 (LC-40)	54 ft	6 ft, 12 ft, 162 ft, 204 ft
108	Delta IV (LC-40)/Falcon 9 (LC-40)	54 ft	6 ft, 12 ft
110	Atlas V/Falcon 9 (LC-40)	54 ft, 162 ft, 204 ft	6 ft, 12 ft
041	Atlas V (LC-41)	230 ft	
393/394	Shuttle (LC-39A)	60 ft	
397/398	Shuttle (LC-39B)	60 ft	
511/512/513	Shuttle Landing Facility	6 ft, 30 ft	

2. Data

The period of record (POR) for the data set was September 2006 – January 2010. The AMU chose September 2006 as the beginning of the POR because the 12-km Weather Research and Forecasting (WRF) model became the operational MesoNAM model in mid-August 2006 and the 45 WS required the AMU conduct the model verification using the “current operational model”.

2.1 Tower Observations

The AMU used the KSC/CCAFS wind tower data from the AMU archive and the AMU wind tower quality control (QC) software to remove erroneous observations from the dataset. Scripts were written in S-PLUS[®] (Insightful Corporation 2007) to import and modify the QC'd wind tower observation files to remove unneeded time periods, observed parameters and sensor heights from the dataset for each tower; and to reformat the files to prepare them for merger with the MesoNAM forecast files. The locations of the towers used for the verification are shown on the map of KSC/CCAFS in Figure 1.

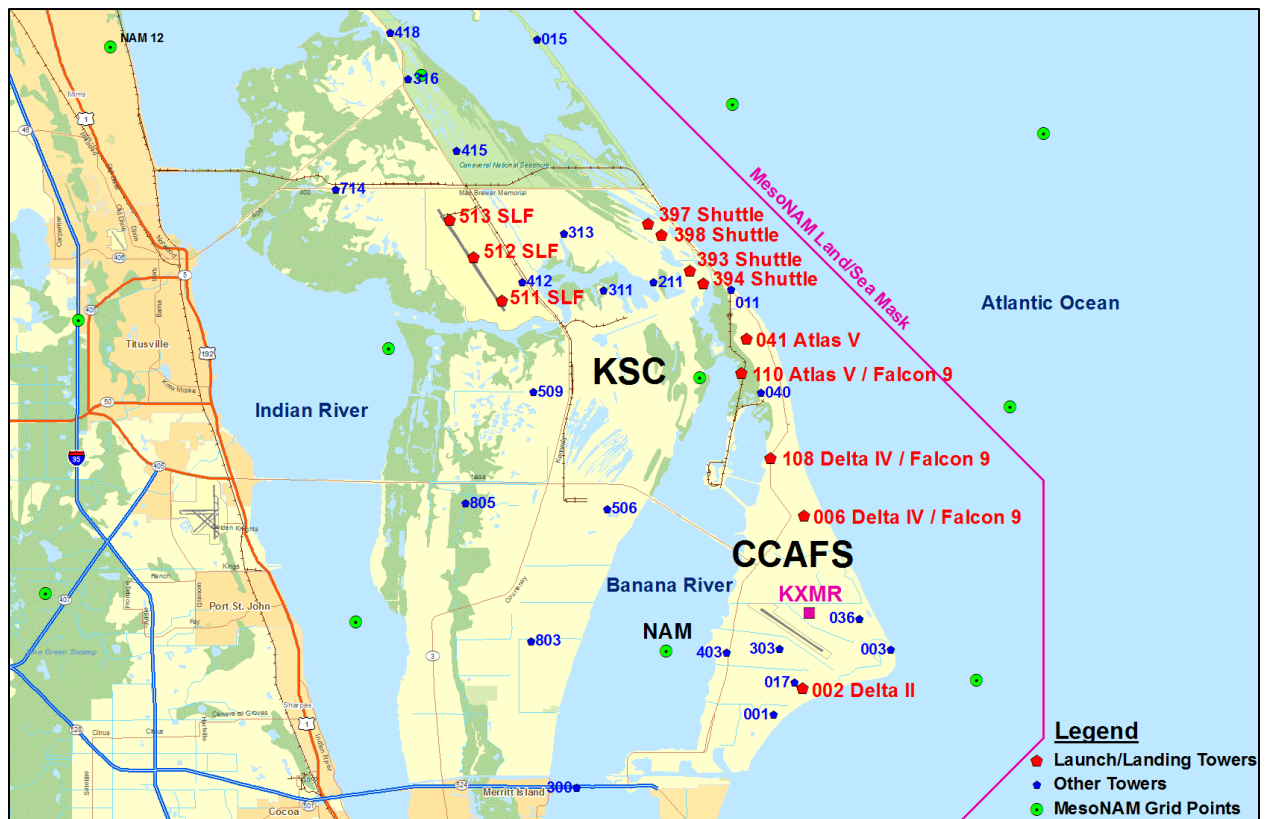


Figure 1. Map of KSC/CCAFS showing the locations of the wind towers used to verify MesoNAM forecasts (red pentagons labeled with tower number and the supported launch activity), the locations of the MesoNAM model grid points (green circles with black dot) and CCAFS weather station (magenta square labeled KXMR). The MesoNAM land/sea mask is shown by the magenta line. The model assumes only land is to the left of the land/sea mask.

Since the tower data were reported every 5 minutes and the MesoNAM forecasts were hourly, the 45 WS requested the AMU calculate the mean value for each observed parameter from the tower data at the top of every hour using the observations from 30 minutes prior and 30 minutes after the hour. The S-PLUS scripts were written to reformat the tower data and calculate the mean values in this manner.

2.2 MesoNAM Forecast Products

The AMU requested and obtained the archived MesoNAM forecasts from ACTA, Inc. The MesoNAM forecast files were provided to the AMU as space-delimited text files. Each file contained the initialization and hourly forecasts to 84 hours at a single model initial time of 00, 06, 12 or 18 UTC. The data were valid at a single point extracted from the model forecasts, identified as "KXMR" in each file. This represents the location of the CCAFS weather station, which is located near the center of CCAFS and is identified in Figure 1 by the magenta square below the CCAFS label. The closest model grid point, which represents the point data used by the 45 WS, is located 3.1 NM southwest of KXMR over the Banana River. It is shown in Figure 1 as a green circle with a black dot and labeled "NAM". Because the grid point is to the left of the model land/sea mask, the model assumes the point is over land.

An inventory of the MesoNAM files in the POR revealed 128 missing files, or model runs, out of a possible 4996 files for the 1249 days. Some days were missing less than four model runs while others were missing all four model runs. The result was a total of 1216 days containing at least one model run.

2.3 Data Stratification

The 45 WS requested the results be stratified by 45°, 90°, 180° and 360° wind sectors, year, warm season (May-September), cool season (October-April), month and model initialization time. They also requested the sector directions be oriented to discriminate between onshore/offshore flow for each tower and to analyze the model forecasts only for the current operational version of the MesoNAM.

After discussions with the 45 WS, the requirement for yearly, warm season and cool season stratifications was rescinded since they believed the monthly stratification would be a better time period to support launch and landing operations. Based on this determination, starting with the smallest wind sector stratification of 45°, the AMU calculated bias statistics for three towers to determine if the sample size was sufficient to be statistically significant, and found it was not. The same was done for the 90° wind sector stratification and the sample size was also too small. Testing a wind sector stratification of 180° indicated the results would produce sufficient sample sizes to calculate monthly statistics. After the AMU provided these test results to the 45 WS, they decided the best 180° stratification for each tower would be calculated as onshore and offshore based on the orientation of the coastline to each tower's location.

3. File Formats

A significant amount of file format manipulation was required in order to compute the required statistics between the observation and model forecast files. In both the observation and forecast data, there were more parameters in the files than required to compute the verification statistics. In order to more efficiently compute the statistics for this large data set, the AMU removed the unneeded parameters, which reduced file sizes, and then reformatted the data within the spreadsheets to reduce the complexity of the task. The goal was to combine the observed and forecast data into Excel format files to compute the statistics and provide the results in a familiar format to the LWOs.

3.1 Tower Observation Files

The raw tower observation files were available in space-delimited text file format. Each file represented one tower and included all sensor heights at all locations (NW and SE side of tower) on that tower. As shown in Figure 2, the format of the files included columns containing, in order left to right, date (year, month, day), time (hour, minute, second), tower identifier (3-digit number), sensor location, sensor height (ft), mean wind direction, mean wind speed (ms^{-1}), peak wind direction, peak wind speed (ms^{-1}), T ($^{\circ}\text{C}$), T_d ($^{\circ}\text{C}$) and relative humidity (%).

	A	B	C	D	E	F	G	H	I	J	K	L
1	Year/Month/Day	Time (HMS)	Tower ID	Sensor Loc	Sensor Hgt	Direction	Spd (m/s)	PDirection	PSpd (m/s)	T (C)	Td (C)	RH (%)

Figure 2. Depiction of column headers for tower observation data contained in the raw data files.

After running the AMU QC program, the tower files were reformatted and output as space-delimited text files and each file contained all sensor heights on a tower on one side of the tower (NW or SE). Figure 3 shows the format of the new QC files that included columns containing, in order left to right, tower identifier (3-digit number), year, day, hour, minute (5-minute intervals), sensor height (ft), T ($^{\circ}\text{F}$), T_d ($^{\circ}\text{F}$), mean wind speed (kt), mean wind direction, peak wind speed (kt), peak wind direction and relative humidity (%).

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1	Tower ID	Year	Month	Day	Hour	Minute	Sensor Hgt	T (F)	Td (F)	Spd (kt)	Direction	PSpd (kt)	PDirection	RH (%)

Figure 3. As in Figure 2 but for the tower observation data as formatted by the AMU QC program.

The S-PLUS scripts mentioned in Section 2.1 were run on the QC'd files to calculate the mean values of wind speed, wind direction, T and T_d at the top of every hour using the observations from 30 minutes prior and 30 minutes after the hour and to output the resulting files in Excel format – one file for every month for each year in the POR. Each file contained data for one sensor height at one sensor location per tower. Figure 4 shows the format of the files with columns containing, in order left to right, year, month, day, hour, mean wind speed (kt), mean wind direction, mean T ($^{\circ}\text{F}$) and mean T_d ($^{\circ}\text{F}$). In preparation for merger with the MesoNAM forecast files, the AMU wrote Microsoft Excel Visual Basic for Applications (VBA) scripts to process the hourly mean files into Excel workbook files containing four spreadsheets per workbook. Each spreadsheet represented the MesoNAM model initialization times of 00, 06, 12 and 18 UTC and contained 84 hourly mean observations to match the 84 hours of model forecasts per model initialization.

	A	B	C	D	E	F	G	H
1	Year	Month	Day	Hour	Mean Spd (kt)	Mean Dir	Mean T (F)	Mean Td (F)

Figure 4. Column format for observation data from an individual tower sensor after hourly mean values were calculated and the files were exported to Excel format.

3.2 MesoNAM Forecast Files

The AMU wrote VBA scripts to import the MesoNAM files into Excel spreadsheets and reformatted them to merge with the wind tower observation spreadsheets. As shown in Figure 5, the format of the raw MesoNAM files included columns containing, in order left to right, date (year, month, day/hour, minute), T (°C), T_d (°C), wind speed (kt), wind direction, mean sea level pressure (mb), low cloud (% coverage), mid cloud (% coverage) and high cloud (% coverage).

	A	B	C	D	E	F	G	H	I
1	YYMMDD/HHMM	T (C)	Td (C)	Spd (kt)	Direction	PMSL	LCLD	MCLD	HCLD

Figure 5. Depiction of column headers for MesoNAM forecast data contained in the raw data files.

Reformatting the raw MesoNAM files included converting the temperature and dew point from Celsius to Fahrenheit and moving rows and columns in the MesoNAM spreadsheets to merge with the wind tower spreadsheets. Figure 6 shows the final format of the column headers depicting the model forecast data that was used in the statistical verification containing, in order left to right, date (year, month, day, hour), wind speed (kt), wind direction, T (°F), T_d (°F)

	A	B	C	D	E
1	YYMMDDHH	WRF Spd	WRF Dir	WRF T	WRF Td

Figure 6. As in Figure 5 but for the MesoNAM forecast data after final reformatting.

3.3 Merged Files

The AMU wrote VBA scripts to create an Excel workbook for each of the 1216 days with at least one model run. The scripts opened the tower observation Excel files and MesoNAM Excel files and merged them to create workbooks that included up to four spreadsheets per workbook, one for each available model run, containing the combined tower observations and MesoNAM forecasts for each sensor on every tower. This resulted in a total of 57,124 workbooks. As shown in Figure 7, the format of the merged files included columns containing, in order left to right, year, month, day, hour, mean wind speed (kt), mean wind direction, mean T (°F) and mean T_d (°F) of the tower observations and date (year, month, day, hour), wind speed (kt), wind direction, T (°F), T_d (°F) of the MesoNAM forecasts.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1	Year	Month	Day	Hour	Mean Spd	Mean Dir	Mean T	Mean Td		YYMMDDHH	WRF Spd	WRF Dir	WRF T	WRF Td

Figure 7. Depiction of column headers for files containing merged tower observation data and MesoNAM forecast data. The observation data was located in columns A-H and the MesoNAM data was located in columns J-N.

4. Verification Statistics

The AMU calculated the verification statistics once the files were properly formatted and stratified. First the difference between all hourly model forecasts and tower observations was calculated and then the mean monthly bias, the standard deviation of the mean monthly bias and then the root mean square error (RMSE). Finally, the hypothesis zero test was applied to the mean monthly bias statistics.

4.1 Statistics

The 45 WS requested the AMU calculate the following statistics to verify the performance of the model against the observations:

- Bias (mean difference),
- Standard deviation of Bias,
- Root Mean Square Error (RMSE), and
- Hypothesis test for Bias = 0.

4.2 Difference Calculations

The model “bias” was calculated for each model forecast against every observation, which represented the difference between the MesoNAM forecast parameters and the tower observation parameters. This difference was calculated by subtracting the observed parameter from the model forecast for each hour of every day in the POR stratified by tower, sensor height and onshore/offshore flow as shown by the equation below.

$$\text{Dif}_{\text{MesoNAM}} = \text{Model Forecast} - \text{Tower Observation}$$

4.2.1 NW and SE Sensors

Before making the difference calculations, the AMU needed to stratify the data into onshore and offshore components. Special care was required when stratifying the observations at Towers 002, 006 and 110 because they have dual sensors located on the NW and SE side of each tower at the same height on the tower. Figure 8 depicts which sensor is chosen to report real-time observations to the forecaster display based on the observed wind direction. The NW sensor is always used when the winds are between 249° and 22° (thick light red arc) and the SE sensor is always used when the winds are between 69° and 203° (thick light green arc). However, both sensors can display observations in the gray arcs, 23° to 68° or 204° to 248°. The sensor used in the gray arc is based on the last sensor used before the winds were in the gray arc. For example, if the SE sensor was the previously selected sensor based on wind direction, then that sensor will continue to be the selected sensor until winds are observed between 248° and 23°. Conversely, if the NW sensor was the previously selected sensor, it will remain so until the winds are observed between 68° and 204°. Data from both sensors are saved for archive regardless of wind direction. For this task, the NW sensor was used for winds between 226° and 45° (thin red arc in Figure 8) and the SE sensor was used for winds between 46° and 225° (thin green arc in Figure 8).

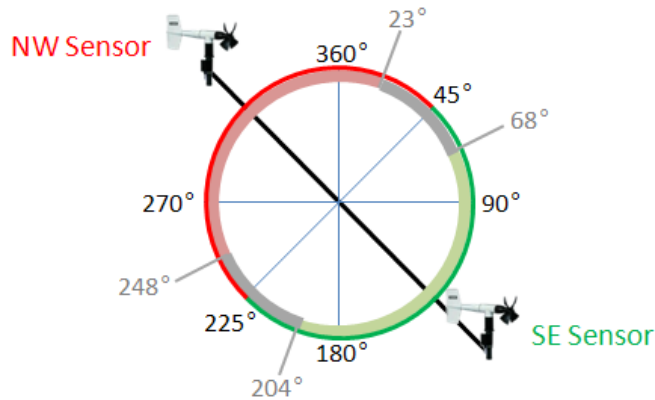


Figure 8. Dual-sensor configuration on Towers 002, 006 and 110. Sensors are mounted on the NW and SE side of each tower. The NW sensor is always selected when the winds are between 249° and 22° (light red arc) and the SE sensor is always selected when the winds are between 69° and 203° (light green arc). Either sensor can be used in the two gray regions when the winds are between 23° and 68° or 204° and 248°.

4.2.2 Onshore/Offshore Directions

Figure 9 shows the locations of Towers 002, 006 and 110 (identified by the green ellipses). The coastline orientation in the vicinity of Tower 002 is northeast to southwest. Therefore, the onshore stratification only used data from the SE sensor and the offshore stratification only used data from the NW sensor. Towers 006 and 110 are affected by a coastline orientation from NW to SE. Therefore, their onshore stratification required using the NW sensor for winds from 316° to 45° and the SE sensor for winds from 46° to 135°. Conversely, their offshore stratification required using the NW sensor for winds from 226° to 315° and the SE sensor for winds from 136° to 225°. To summarize the sensor configurations for onshore and offshore flow for the dual-sensor towers:

For Tower 002:

- Onshore: SE sensor 46° to 225°
- Offshore: NW sensor 226° to 45°

For Towers 006 and 110:

- Onshore: NW sensor 316° to 45° and SE sensor, 46° to 135°
- Offshore: NW sensor 226° to 315° and SE sensor 136° to 225°

The AMU developed VBA scripts that select the appropriate sensors for the onshore and offshore calculations for the dual-sensor towers.



Figure 9. Map of KSC/CCAFS showing the locations of the wind towers used to verify MesoNAM forecasts (red pentagons labeled with tower number and the supported launch activity) and the dual-sensor towers (green ellipses). The onshore and offshore stratifications were determined by the coastline alignment relative to the Atlantic Ocean for each tower.

The wind tower configurations at the Shuttle pads presented a similar challenge to computing onshore and offshore statistics as for the dual-sensor towers. As Figure 9 shows, Tower 393 (Pad 39A) and Tower 397 (Pad 39B) are on the NW side of each pad and have sensors mounted on the NW side of each tower. Tower 394 (Pad 39A) and Tower 398 (Pad 39B) are on the SE side of each pad and have sensors mounted on the SE side of each tower. This sensor configuration is similar to that described above for the dual-sensor towers except the sensors are not on the same tower. The AMU also developed VBA scripts to extract the appropriate data from each of these towers and then combine the data at each pad to compute statistics for the onshore and offshore components.

4.2.3 Onshore/Offshore Differences

Using the Excel files with the merged tower observations and MesoNAM forecasts, the AMU-developed VBA scripts calculated the difference of wind speed, wind direction, T and T_d based on the onshore and offshore wind direction stratifications. The scripts opened a merged Excel workbook file, calculated the difference and entered the results in columns P-S. Figure 10 shows an example of an offshore stratification worksheet from Tower 002. The difference was not calculated in rows 23-25 and 47-51 because the mean wind direction was onshore at those times, as shown in the green ellipses in column F.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
1	Year	Month	Day	Hour	Mean Spd	Mean Dir	Mean T	Mean Td		YYMMDDHH	WRF Spd	WRF Dir	WRF T	WRF Td		Bias Spd	Bias Dir	Bias T	Bias Td
2	2007	4	7	0	3.3	5	66.2	45.5		070407/0000	5.9	304	65.5	30.6		2.6	-60.9	-0.7	-14.9
3	2007	4	7	1	4.4	351	65.1	46.1		070407/0100	9.3	287	62.6	34.2		4.9	63.5	-2.5	-12.0
4	2007	4	7	2	6.1	316	63.4	47.9		070407/0200	12.1	282	60.3	32.7		6.0	34.1	-3.2	-15.2
5	2007	4	7	3	11.1	288	62.8	44.0		070407/0300	16.7	282	60.3	34.2		5.6	6.3	-2.5	-9.9
6	2007	4	7	4	8.9	291	60.6	45.5		070407/0400	16.7	285	59.0	35.6		7.8	6.2	-1.6	-9.9
7	2007	4	7	5	8.6	299	59.7	43.6		070407/0500	16.2	296	58.1	36.5		7.6	2.6	-1.6	-7.1
8	2007	4	7	6	8.4	302	58.6	43.0		070407/0600	15.9	297	56.5	35.1		7.5	5.1	-2.2	-8.0
9	2007	4	7	7	9.4	308	58.4	42.3		070407/0700	16.2	304	55.2	33.1		6.8	3.9	-3.2	-9.2
10	2007	4	7	8	9.7	321	57.6	40.6		070407/0800	17.9	313	55.0	31.3		8.2	8.1	-2.6	-9.3
11	2007	4	7	9	9.8	326	55.8	40.0		070407/0900	18.3	317	54.3	29.5		8.5	9.5	-1.5	-10.5
12	2007	4	7	10	10.2	324	54.8	38.8		070407/1000	18.3	319	53.2	28.2		8.1	5.0	-1.5	-10.6
13	2007	4	7	11	10.0	320	54.1	38.7		070407/1100	17.9	319	52.3	28.0		7.9	1.2	-1.8	-10.7
14	2007	4	7	12	10.9	320	54.0	37.7		070407/1200	18.3	318	53.6	29.8		7.4	2.3	-0.4	-7.9
15	2007	4	7	13	11.6	321	54.7	36.7		070407/1300	19.8	325	57.0	32.4		8.2	-3.8	2.3	-4.3
16	2007	4	7	14	11.8	328	56.2	35.1		070407/1400	18.4	330	59.2	33.6		6.6	-2.4	3.0	-1.5
17	2007	4	7	15	10.9	321	58.0	35.8		070407/1500	17.2	333	61.2	35.4		6.3	-12.2	3.2	-0.4
18	2007	4	7	16	8.1	313	59.2	36.3		070407/1600	16.5	336	62.4	36.0		8.4	-23.4	3.2	-0.3
19	2007	4	7	17	7.0	311	60.9	35.8		070407/1700	14.8	341	63.5	36.7		7.8	-30.0	2.6	0.9
20	2007	4	7	18	6.9	313	62.7	35.0		070407/1800	13.8	340	64.0	36.1		6.9	-27.5	1.3	1.1
21	2007	4	7	19	10.0	29	61.0	41.9		070407/1900	11.4	339	64.6	35.1		1.4	-49.5	3.6	-6.8
22	2007	4	7	20	9.4	38	60.8	42.3		070407/2000	8.3	339	64.9	34.3		-1.1	-59.1	4.1	-7.9
23	2007	4	7	21	8.4	48	60.7	42.6		070407/2100	6.4	340	65.3	33.6					
24	2007	4	7	22	8.1	46	60.3	42.6		070407/2200	6.3	351	64.8	33.1					
25	2007	4	7	23	5.2	47	59.8	43.0		070407/2300	5.8	358	63.0	33.4					
26	2007	4	8	0	4.1	42	58.5	44.1		070408/0000	6.5	9	57.7	33.8		2.4	32.8	-0.8	-10.3
27	2007	4	8	1	3.0	10	58.3	44.2		070408/0100	6.2	5	56.1	34.9		3.2	5.3	-2.2	-9.3
28	2007	4	8	2	3.5	339	59.0	43.9		070408/0200	6.4	357	54.9	34.9		2.9	-18.3	-4.2	-9.0
29	2007	4	8	3	4.1	331	59.0	44.2		070408/0300	6.6	339	53.4	32.7		2.5	-7.7	-5.6	-11.5
30	2007	4	8	4	6.7	291	56.5	43.8		070408/0400	8.6	322	52.5	28.2		1.9	-31.0	-4.0	-15.5
31	2007	4	8	5	7.5	298	55.0	42.1		070408/0500	10.7	318	51.1	25.9		3.2	-19.7	-4.0	-16.3
32	2007	4	8	6	7.7	306	54.0	41.4		070408/0600	12.0	320	50.4	23.4		4.3	-14.3	-3.6	-18.1
33	2007	4	8	7	7.8	309	53.2	41.3		070408/0700	12.4	321	50.0	21.7		4.6	-12.5	-3.2	-19.5
34	2007	4	8	8	8.4	324	52.9	36.5		070408/0800	12.6	323	49.5	21.4		4.2	1.4	-3.5	-15.1
35	2007	4	8	9	7.5	323	52.8	33.9		070408/0900	12.0	329	48.9	21.7		4.5	-5.9	-3.9	-12.2
36	2007	4	8	10	6.5	317	53.5	34.2		070408/1000	11.8	329	48.6	22.6		5.3	-11.6	-4.9	-11.6
37	2007	4	8	11	7.0	318	53.9	34.9		070408/1100	9.9	332	47.8	22.8		2.9	-13.5	-6.1	-12.0
38	2007	4	8	12	7.3	328	53.7	36.0		070408/1200	9.3	334	52.0	27.3		2.0	-6.4	-1.7	-8.6
39	2007	4	8	13	7.1	328	55.3	36.4		070408/1300	9.7	345	58.6	35.8		2.6	-16.6	3.3	-0.6
40	2007	4	8	14	8.4	326	58.4	34.0		070408/1400	10.2	346	61.3	38.1		1.8	-19.9	3.0	4.1
41	2007	4	8	15	6.9	328	60.3	33.6		070408/1500	8.8	347	62.2	38.7		1.9	-19.4	1.9	5.0
42	2007	4	8	16	6.0	332	61.6	34.2		070408/1600	8.2	345	60.8	38.7		2.2	-12.6	-0.8	4.4
43	2007	4	8	17	3.3	333	63.1	36.8		070408/1700	8.8	351	60.4	39.2		5.5	-18.3	-2.7	2.4
44	2007	4	8	18	6.5	39	63.4	43.0		070408/1800	7.4	357	60.8	40.5		0.9	-42.5	-2.6	-2.5
45	2007	4	8	19	5.7	16	64.1	42.5		070408/1900	11.9	323	58.6	40.8		6.2	-52.6	-5.4	-1.6
46	2007	4	8	20	7.8	34	63.6	43.6		070408/2000	14.1	314	50.9	44.8		6.3	-80.0	-12.7	1.2
47	2007	4	8	21	6.6	64	63.3	44.4		070408/2100	13.6	317	49.5	44.1					
48	2007	4	8	22	5.6	59	63.0	44.7		070408/2200	9.7	323	48.7	44.6					
49	2007	4	8	23	3.7	57	62.5	45.0		070408/2300	6.8	309	49.1	45.1					
50	2007	4	9	0	3.9	60	61.4	46.0		070409/0000	6.1	287	48.6	45.9					
51	2007	4	9	1	2.4	80	62.2	46.5		070409/0100	4.4	257	48.7	46.0					
52	2007	4	9	2	0.1	350	62.8	47.5		070409/0200	4.9	275	49.5	46.6		4.8	75.0	-13.3	-1.0
53	2007	4	9	3	1.8	8	62.9	47.6		070409/0300	5.8	290	49.5	46.9		4.0	-78.0	-13.4	-0.6
54	2007	4	9	4	2.4	343	63.2	47.8		070409/0400	6.6	298	49.6	47.3		4.2	44.8	-13.6	-0.5
55	2007	4	9	5	2.0	348	63.0	48.2		070409/0500	6.8	204	50.0	47.2		3.8	16.8	-12.0	0.0

Figure 10. Example of a merged Excel workbook file showing the tower observations from Tower 002 (columns A-H), MesoNAM forecasts (columns J-N) initialized at 00 UTC (00Z tab at bottom left), and difference calculations (columns P-S) for an offshore stratification

The procedures to calculate the difference included quality checks and stratification calculations. In the VBA scripts, the first step implemented was a QC test that ensured the tower observations did not exceed unrealistic values and/or climatological maxima and minima based on a 30-year Operational Climatic Data Summary provided by the 14th Weather Squadron for the Shuttle Landing Facility (KTTS). Even though an initial QC was performed on the raw observational data, through visual inspection, the AMU discovered some out-of-bounds observations were still present after the initial QC. The VBA script QC test checked to ensure the observations were within the following ranges:

- Mean wind direction $\geq 0^\circ$ and $\leq 360^\circ$,
- Mean wind speed ≥ 0 kt and ≤ 65 kt,
- Mean T ≥ 20 °F and ≤ 100 °F, and
- Mean T_d ≥ 5 °F and ≤ 85 °F.

4.2.4 Coastline Orientation

To stratify the onshore and offshore flow, the AMU scripts accounted for the orientation of the coastline differences between Tower 002 and the rest of the towers. For T and T_d sensors without corresponding wind sensors at the same height, the wind sensors closest to the T and T_d sensors were used

to determine the stratification for those observations. For example, the 12 ft wind sensors were used for the 6 ft T and T_d sensors.

To calculate the proper stratification for Tower 002, the AMU scripts checked the mean wind direction associated with each parameter prior to every difference calculation. Separate calculations were made for the sensors on the NW and SE sides of the tower. For onshore flow, the scripts verified the mean wind direction observed was $\geq 45^\circ$ and $< 225^\circ$, represented by the green arrows and arc in Figure 11. In this case, data from the SE sensor were used. For offshore flow, the NW sensor was used if the scripts verified the mean wind direction observed was $\geq 225^\circ$ and $\leq 360^\circ$ or $< 45^\circ$, represented by the red arrows and arc in Figure 11.

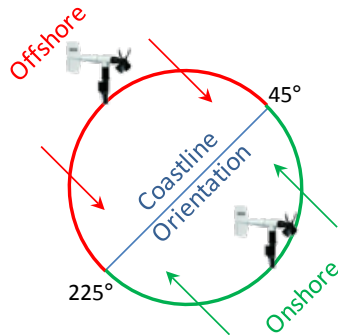


Figure 11. Representation of the sensor configuration for onshore and offshore stratifications on the dual-sensor Tower 002. The NW sensor is used for offshore flow stratification while the SE sensor is used for onshore flow stratification.

To calculate the proper stratification for the other two dual-sensor towers, Towers 006 and 110, the AMU scripts also checked the mean wind direction associated with each parameter prior to every difference calculation and made separate calculations for the sensors on the NW and SE sides of the tower. Because of the towers' orientation to the coastline, sensors on either side could be used for both onshore and offshore stratifications, which required using NW and SE sensors to determine the stratification. For onshore flow, the NW sensor was used if the mean wind direction was $\geq 315^\circ$ or $< 45^\circ$, represented by a green arrow and thick light green arc in Figure 12. The SE sensor was used if the mean wind direction was $\geq 45^\circ$ and $< 135^\circ$, represented a green arrow and thick dark green arc in Figure 12. For offshore flow, the NW sensor was used if the mean wind direction was $\geq 225^\circ$ and $< 315^\circ$, represented by a red arrow and thick light red arc in Figure 12. The SE sensor was used if the mean wind direction was $\geq 135^\circ$ and $< 225^\circ$, represented by the red arrow and thick dark red arc in Figure 12.

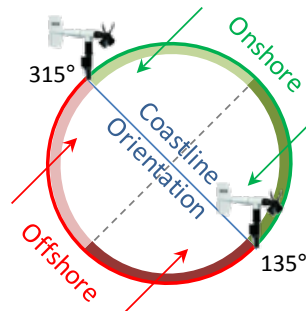


Figure 12. As in Figure 11 but for the dual-sensor Towers 006 and 110. Both the NW and SE sensors must be used for onshore and offshore flow stratifications. The gray dashed line represents the divide between the data used from the NW sensor and from SE sensor.

As with the dual-sensor towers, the AMU scripts checked the mean wind direction associated with each parameter from the single-sensor towers prior to every difference calculation for the towers with one sensor at a specified height. For onshore flow, the scripts verified the mean wind direction observed at the sensor was $\geq 315^\circ$ or $< 135^\circ$, represented by the green arrows and arc in Figure 13. For offshore flow, the scripts verified the mean wind direction observed at the sensor was $\geq 135^\circ$ and $< 315^\circ$, represented by the red arrows and arc in Figure 13.

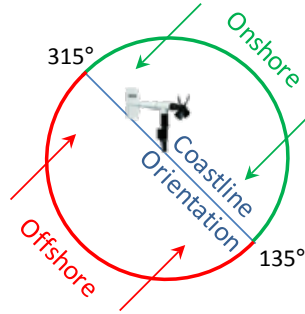


Figure 13. As in Figure 11 but for the single-sensor towers. A single sensor was used for both onshore and offshore stratifications.

4.3 Mean Monthly Model Bias Calculations

The mean monthly model bias statistics were calculated using the previously computed hourly differences between the model forecast parameters and tower observation parameters. As discussed in Section 4.2, the model bias statistics were calculated in the master Excel workbook files and displayed in columns C-F as shown in Figure 15 by using the following equation:

$$Bias_{MesoNAM\ Monthly\ Mean} = \frac{1}{n} \sum_{i=1}^n (f_i - o_i)$$

Where:

n = number of available model forecasts in any given stratification,

f = MesoNAM forecast of T, T_d , wind speed or wind direction, and

o = observed T, T_d , wind speed or wind direction from each tower/sensor height.

4.4 Standard Deviation of Mean Monthly Bias Calculations

The model standard deviation of mean monthly bias statistics were calculated using the previously computed mean monthly bias and using the following equation:

$$STDEV_{MesoNAM\ Bias} = \sqrt{\frac{\sum(x - \bar{x})^2}{n}}$$

Where:

n = number of available model forecasts in any given stratification,

x = model bias of each forecast,

\bar{x} = mean bias of each forecast period in any given stratification (Section 4.3).

4.5 Root Mean Square Error Calculations

The model root mean square error (RMSE) was calculated using the following equations:

$$RMSE = \sqrt{MSE}$$
$$MSE = \frac{1}{n} \sum_{i=1}^n (f_i - o_i)^2$$

Where:

n = number of available model forecasts in any given stratification,

f = MesoNAM forecast of T, T_d, wind speed or wind direction, and

o = observed T, T_d, wind speed or wind direction from each tower/sensor height.

4.6 Hypothesis Zero Test

Hypothesis testing uses statistics to determine the probability that a given hypothesis is true. The AMU worked with the 45 WS to determine the best way to setup the test. The goal was to determine if the model bias of any of the parameters assessed throughout the model forecast period was not statistically significantly different from zero. The 45 WS recommended the test statistic for this data set would be to divide the mean bias of a given parameter by its mean standard deviation divided by the square root of the number of observations within a given stratification (onshore or offshore), as shown by:

$$\frac{\text{Mean Bias}}{\frac{\text{Mean STDEV}}{\sqrt{n}}}$$

Where

Mean Bias as defined in Section 4.3,

Mean STDEV as defined in Section 4.4, and

n = number of observations.

If this equation produced a value ≥ -1.96 or ≤ 1.96 (personal communication, Mr. Roeder, 45 WS) for a data point, then the bias at that point was not statistically significantly different from zero and the model forecast for that point was considered to have no error.

The AMU worked closely with the 45 WS LWOs to determine the best way to display the results of the hypothesis zero test graphically so it would be useful for operations. The group agreed to have the hypothesis zero test displayed on the model bias charts as shaded regions only when the test was true ($-1.96 \leq \text{test value} \leq 1.96$). When the test was true, it indicated that even though the bias may not have been zero at any given data point, statistically the bias was zero.

In Figure 14, there are several time periods when the hypothesis zero test was true as indicated by the green shading. The shape of the green shading is defined by the test value when the test was true. For an operational example, consider the forecast valid time 73-83 hr indicated by a red ellipse in Figure 14. Even though the model temperature bias (blue line) was not zero, the hypothesis zero test indicated that statistically, the temperature bias was zero and the LWO would not have to adjust the model temperature forecast for this time period. When the hypothesis zero test was false, the graph was not shaded and the LWO would have to consider adjusting the model forecast temperature. An example of a false hypothesis zero test is shown by a purple ellipse in Figure 14 during the 61-72 hr forecast valid time.

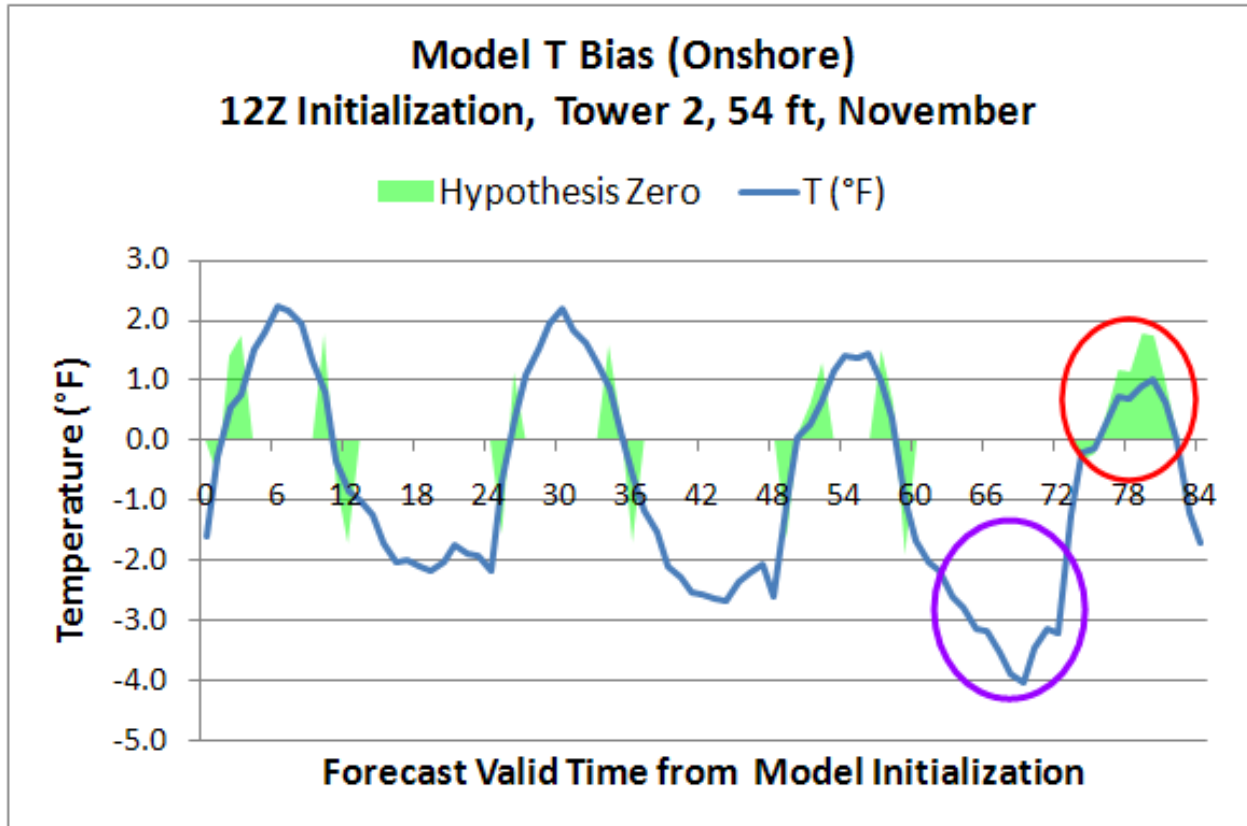


Figure 14. An example of a verification chart showing model bias of T (blue line) and hypothesis zero test = true (light green shaded regions) from a 12 UTC model initialization using observations from Tower 2 at 54 ft for November with an onshore stratification. The red and purple ellipses highlight the region of the chart in the example discussed in the text.

4.7 Statistics Values

The AMU developed master files in Excel workbook format stratified by tower, sensor height, onshore/offshore flow and month in order to calculate the statistics. Figure 15 shows a portion of one of the master files for Tower 006 at 54 ft during offshore flow in June 2007-2009. Each master file contains four spreadsheets representing the model initialization times of 00, 06, 12 and 18 UTC. In each spreadsheet, column A shows the month, tower/sensor identification, sensor height and model initialization time and column B shows the model forecast hour, 0-84. Columns C-F contain the model bias, columns H-K contain the model standard deviation of the bias, and columns M-P contain the model RMSE for the month for each model forecast hour based on the formulas in each cell. The columns beginning with R contain the differences for each parameter that were previously calculated for each day of every month in the POR and each model forecast hour.

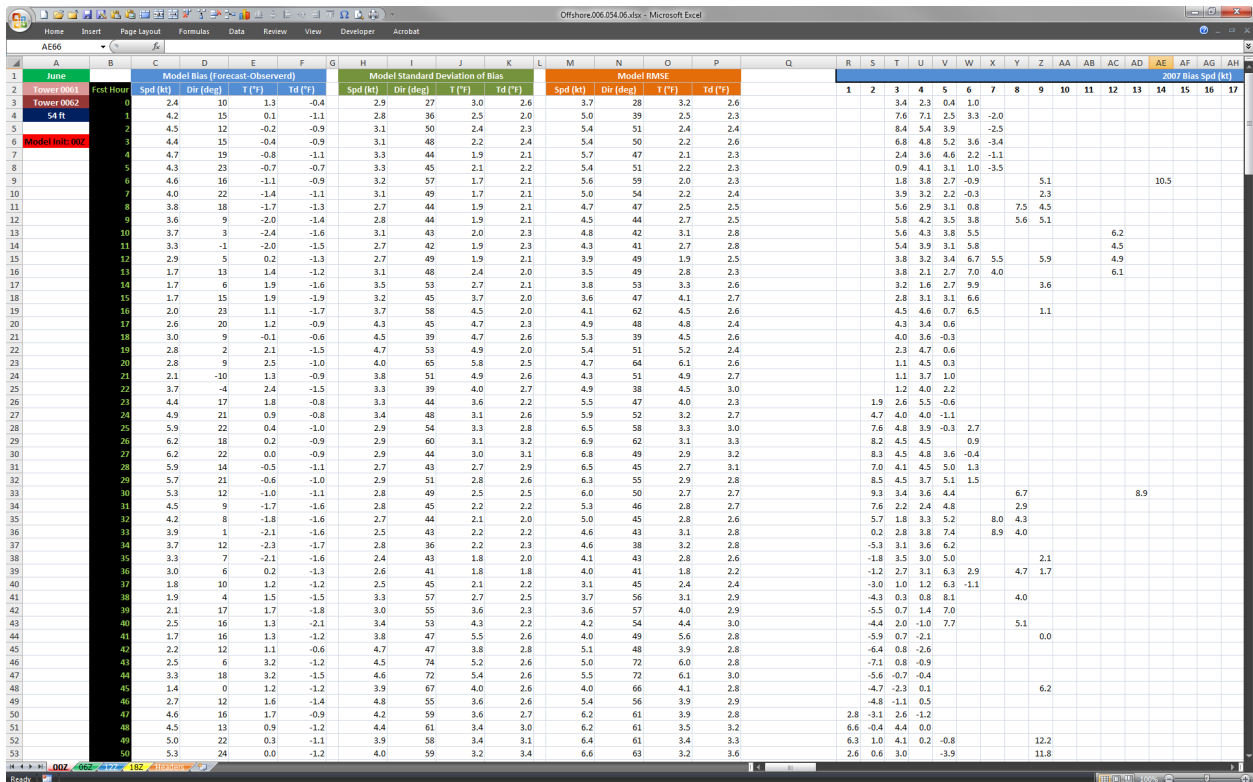


Figure 15. Example of a master Excel workbook file used to calculate the mean monthly statistics. Column A contains tower, sensor identification and model initialization information, column B shows the model forecast hour, columns C-P include the calculated statistics and the rest of the spreadsheet holds the hourly difference calculations.

The AMU created charts in each spreadsheet that were automatically populated with the statistics by a VBA script that extracted the difference calculations from the merged spreadsheets and saved them in the master workbook files. Figure 16 shows the same spreadsheet as in Figure 15 but it is displaying several of the resulting charts based on the statistics calculated within the spreadsheet. The charts in the master workbooks were ultimately used to populate the graphical user interface (GUI) described in Section 6.

5. Model Performance

The goal of this work was to provide the LWOs with a tool to evaluate model performance compared to observations at the tower(s) used to support a specific launch vehicle and not to evaluate the overall model performance at KSC/CCAFS. However, it is worth mentioning several characteristics of the model that were noted during this work.

5.1 Accuracy

As one would expect, the model's accuracy decreased as the forecast valid time from the model initialization increased. Figure 17a and Figure 17b show examples of the model's standard deviations of wind speed bias and wind direction bias, respectively. The trend line in both figures illustrates the increasing error in the model forecast compared to the wind observations. This model characteristic was noted in most of the data.

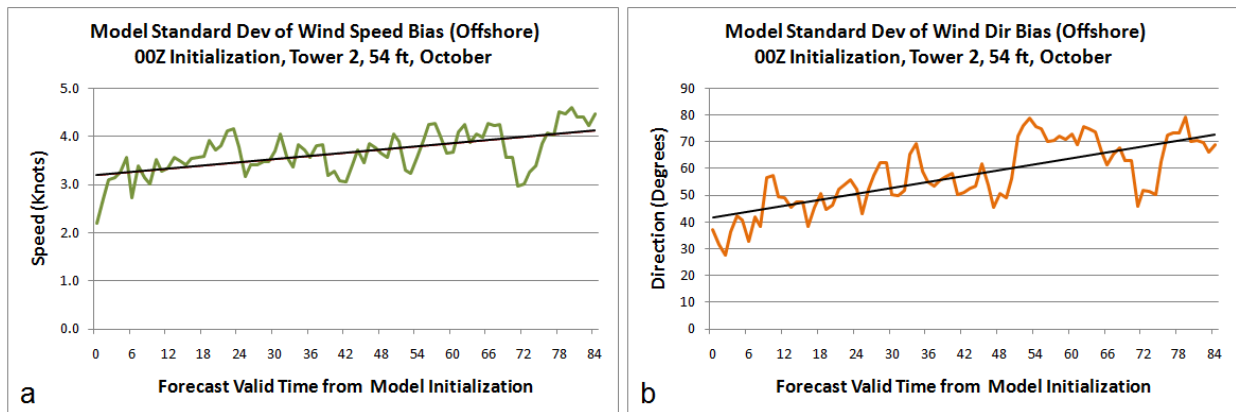


Figure 17. An example of verification charts illustrating the model's increasing error (solid black trend lines) for (a) the model standard deviation of wind speed bias (green line) and (b) standard deviation of wind direction bias (orange line) using observations from Tower 002 at 54 ft for October with an offshore stratification.

5.2 Diurnal Signal

A diurnal signal was present in the T and T_d model bias as shown by the examples in Figure 18 and Figure 19. The diurnal signal was pervasive among the towers at varying degrees of amplitude. In general, the model had a cool T bias during the late night (~ 05-07 UTC) and a warm T bias during the afternoon (~ 17-19 UTC). The T_d showed the opposite – the high bias during the late night and low bias during the afternoon.

Figure 18a illustrates an example of the T bias at Tower 006 for a model initialization time of 00 UTC, while Figure 18b is an example of the T bias for a model initialization time of 12 UTC for the same tower, sensor height, month and onshore stratification. These charts show that the model's warm bias peaked at the 18, 42 and 66 hr forecast valid times from the 00 UTC initialization, and at the 6, 30, 54 and 78 hr forecast valid times from the 12 UTC initialization. For both initialization times, the warm bias maxima occurred at about 18 UTC throughout the forecast. Conversely, the cool bias minima were at the 29, 53 and 77 hr forecast valid times from the 00 UTC initialization, and at the 17, 41 and 65 hr forecast valid times from the 12 UTC initialization. For both initialization times, the cool bias minima occurred at about 06 UTC throughout the forecast.

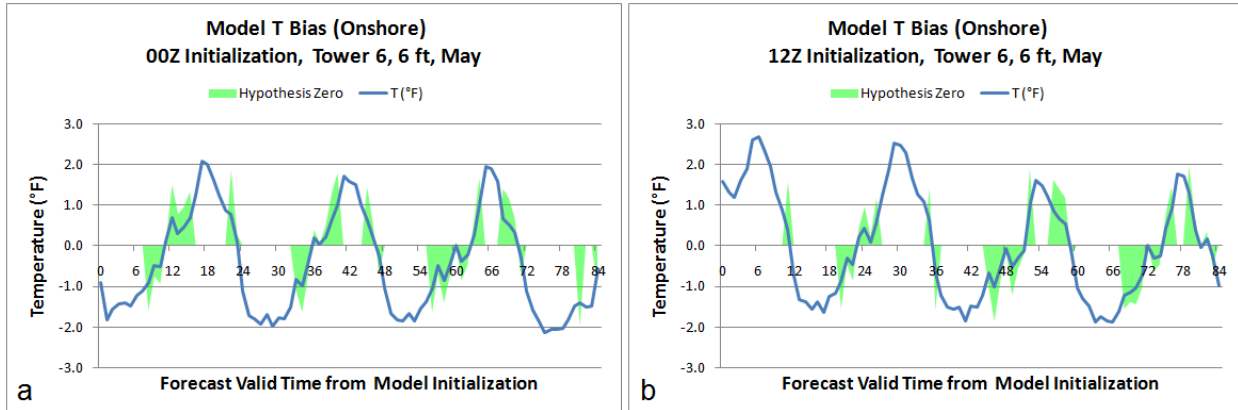


Figure 18. An example of verification charts illustrating the model’s diurnal signal for the model bias of T (blue line) and hypothesis zero test = true (light green shaded regions) (a) from a 00 UTC model initialization and (b) from a 12 UTC model initialization using observations from Tower 006 at 6 ft for May with an onshore stratification.

Examples of the model’s diurnal T_d signal is shown in Figure 19a and Figure 19b and are valid for the same tower, sensor height, month and onshore stratification as in Figure 18. While showing a similar pattern to T, the T_d high and low biases occurred during the late night and afternoon, respectively, which was opposite of T. Figure 19a illustrates an example of the T_d bias for a model initialization time of 00 UTC, while Figure 19b is an example of the T_d bias for a model initialization time of 12 UTC.

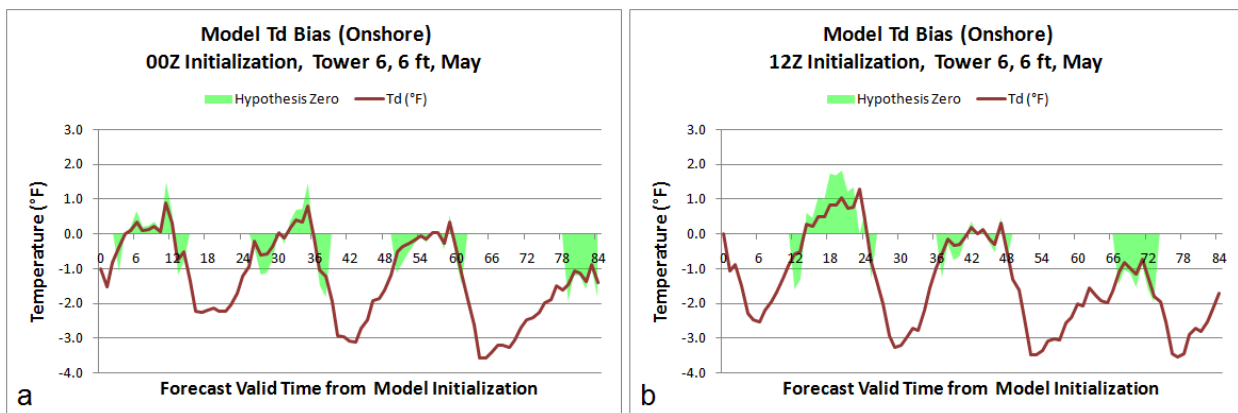


Figure 19. As in Figure 18 but for T_d .

5.3 Model Parameter Vertical Level and Sensor Height

The MesoNAM outputs forecast temperature and winds at heights of 2 m (~ 7 ft) and 10 m (~ 33 ft), respectively. In general, the model bias of T was smaller at a tower sensor height of 6 ft and larger at higher levels. The charts in Figure 20 illustrate this showing the model bias of $T \leq |2.4 \text{ } ^\circ\text{F}|$ at 6 ft (Figure 20a) and the bias of $T \leq |4.0 \text{ } ^\circ\text{F}|$ at 54 ft (Figure 20b) at Tower 002.

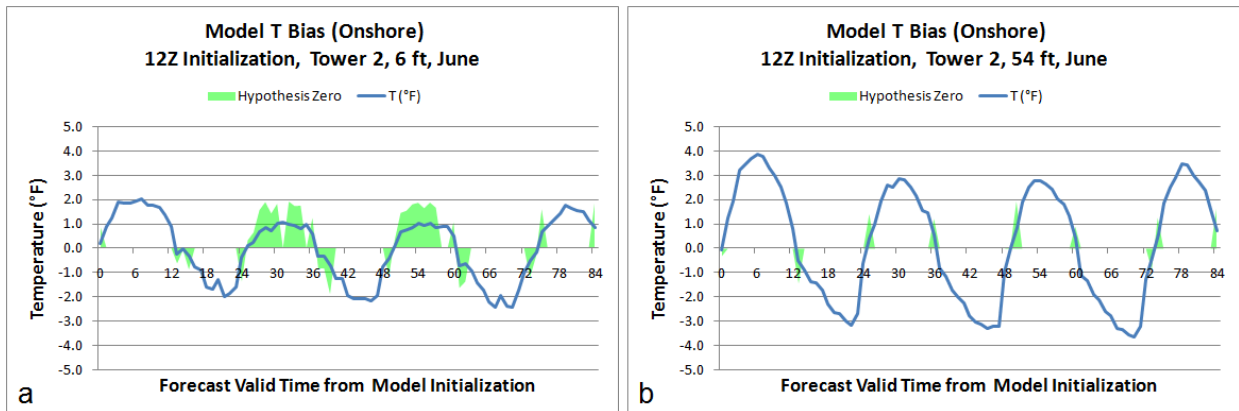


Figure 20. An example of verification charts illustrating how the model’s bias varies with respect to tower sensor height for the model bias of T (blue line) and hypothesis zero test = true (light green shaded regions) from (a) the 6 ft sensor height and (b) the 54 ft sensor height using observations from Tower 002 for June with an onshore stratification.

Figure 21 illustrates how the model bias of wind speed differs at two different levels on Tower 002. At the higher sensor height of 54 ft (Figure 21a) the wind speed bias was < 5 kt while at the lower sensor height of 12 ft (Figure 21b) the bias was < 8 kt. In general, the wind speed bias was smaller at tower sensor heights above 54 ft and larger at 12 ft.

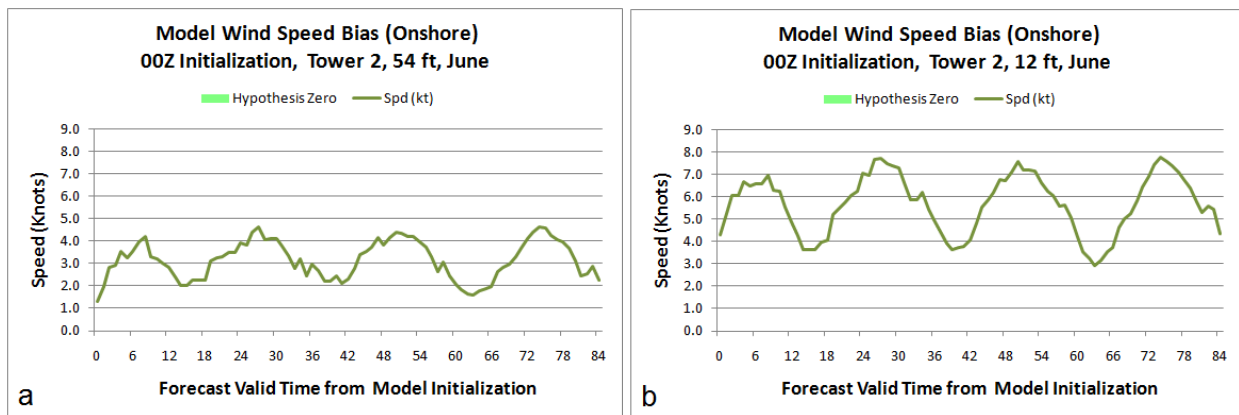


Figure 21. An example of verification charts illustrating how the model’s bias varies with respect to tower sensor height for (a) the model bias of wind speed (green line) from the 54 ft sensor height and (b) the 12 ft sensor height using observations from Tower 2 for June with an onshore stratification.

6. MesoNAM Verification Tool Graphical User Interface

The dataset for this work contains 2,496 Excel spreadsheets with 4,896 charts. In order to present the data to the LWOs in a manageable and user-friendly manner, the AMU developed the MesoNAM Verification Tool using a Hyper-Text Markup Language (HTML) GUI so the tool could be used in most popular web browsers with computers running different operating systems such as Microsoft Windows and Linux.

For easy navigation, the AMU implemented a multi-level drop-down menu written in JavaScript embedded within the HTML code. The main page of the GUI is shown in Figure 22. The title at the top of the page defines the name, version and date of the tool. The drop-down navigation menu is located under the title and allows the user to choose data by placing their mouse pointer over the desired tower/site to display a drop-down menu. A map of KSC/CCAFS showing the locations of the wind towers used to verify MesoNAM forecasts, the locations of the MesoNAM model grid points, the CCAFS weather station (KXMR) and the MesoNAM land/sea mask is shown as a reference for the LWOs.

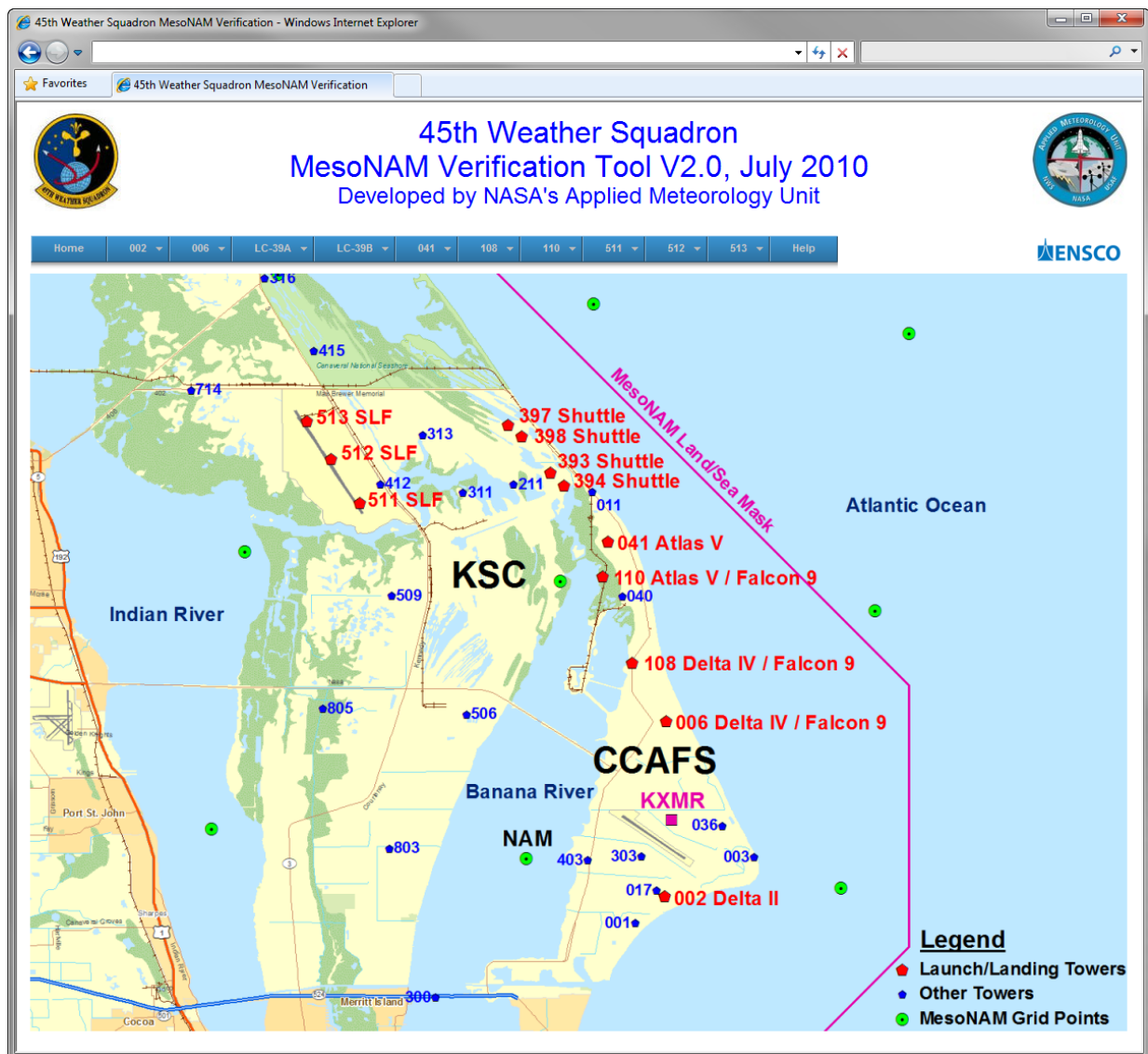


Figure 22. Main page of the GUI in a web browser showing the basic layout of the GUI.

An illustration of the drop-down menu is shown in Figure 23. Assume a user placed their mouse pointer over the menu item for Tower 002. By doing so, this displayed the first level of the drop-down menu, the months January- December. The user then moved the mouse pointer over November, the 12Z model initialization time, 54 ft sensor height, and then clicked "Onshore" for the flow.

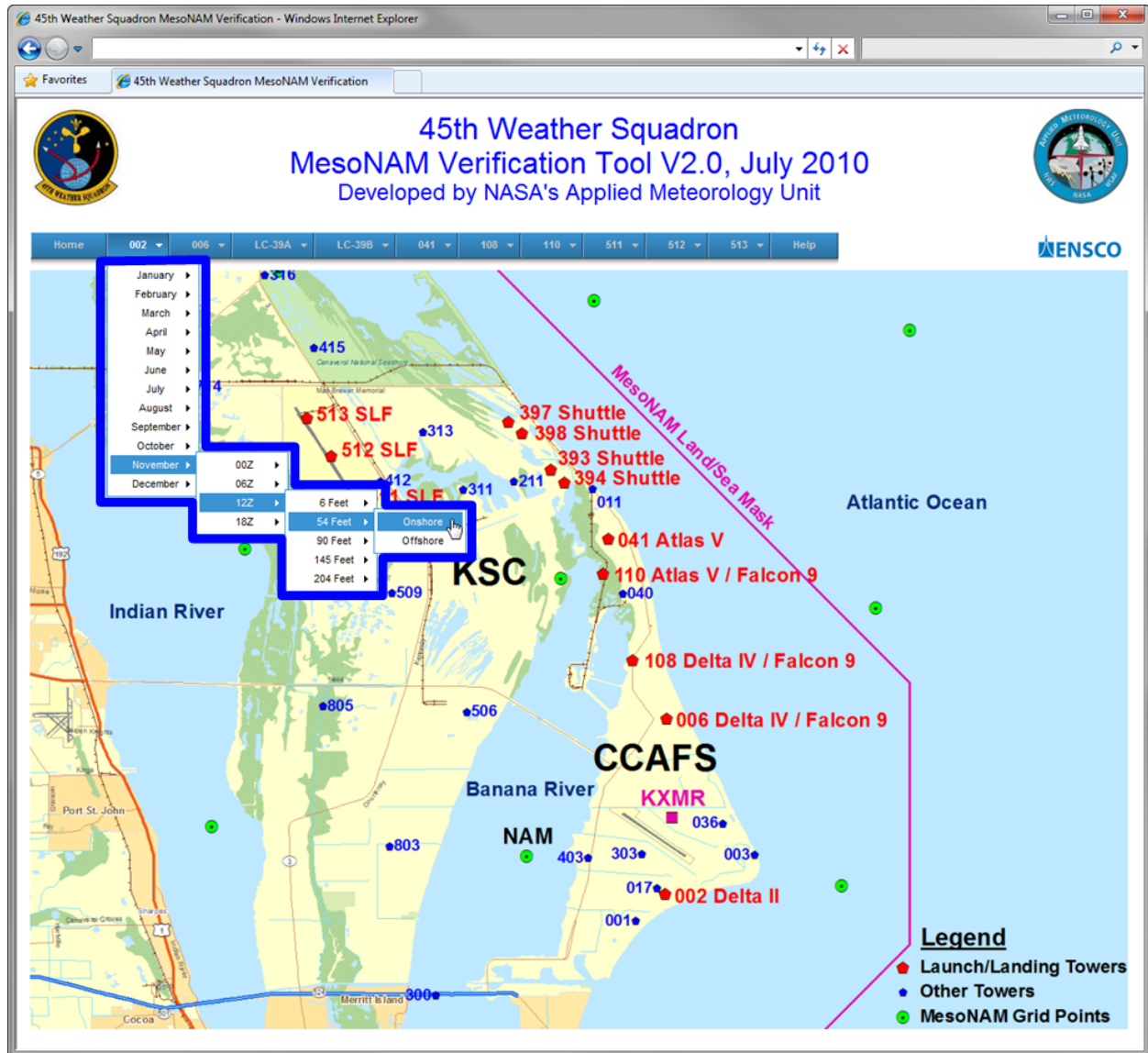


Figure 23. Main page of the GUI illustrating the functionality of the drop-down menu (heavy blue polygon region).

The resulting page in the GUI displayed from these choices is shown in Figure 24. It contains charts showing the model bias, standard deviation of bias and RMSE of T, T_d, wind speed and wind direction for onshore flow at a sensor height of 54 ft based on a 12 UTC model initialization for November at Tower 002. The LWO can view all of the charts by using the vertical scroll bar on the right side of the web page. On each web page in the tool, the AMU added a link to the corresponding Excel workbook file that produced the charts on that page. This feature allows the user to view the spreadsheets from which the charts were derived. As shown in Figure 24, there is an Excel icon (red ellipse) just under the "Home" link on the navigation menu. When the user clicks the link, Excel opens the workbook file associated with the charts on that web page.

The AMU included a "Help/About" page as part of the GUI that briefly explains why it was developed, how to use it, sensor configuration and a description of the data (Figure 25). The link to this page is on the far right of the drop-down menu bar on the main page. The Help page includes sections describing the final report and how to access it, background information on the task, how to use the tool and the data used.

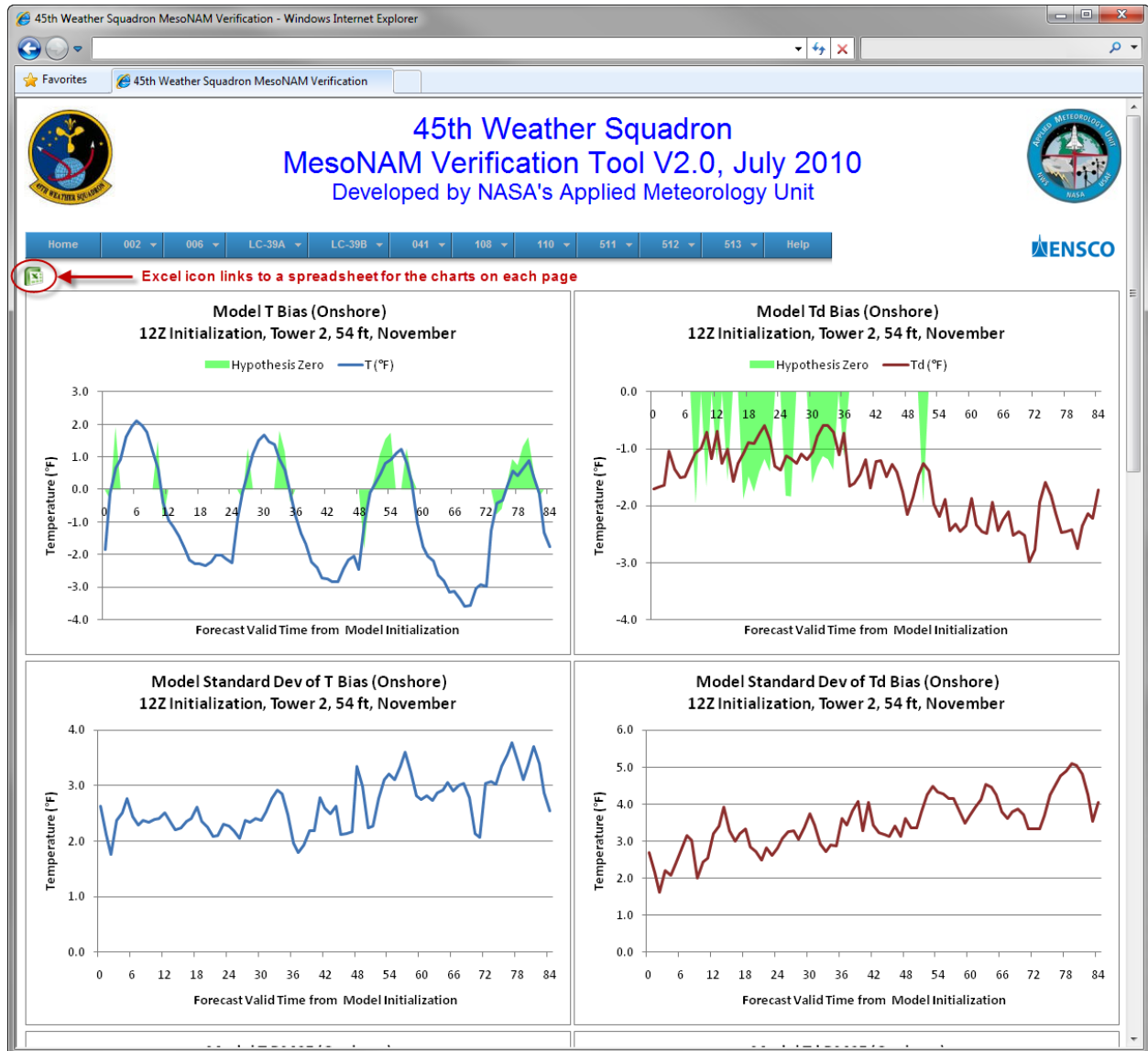



Figure 24. A page from the GUI displaying four charts of model T bias and standard deviation of bias and model T_d bias and standard deviation of bias for Tower 002 at a sensor height of 54 ft for a 12 UTC model initialization for November. The blue lines characterize T and the red lines T_d . The green shaded regions correspond to a “true” hypothesis zero test. The icon representing a link to access the Excel file used to create the charts is shown within the red ellipse under the blue menu bar.

45th Weather Squadron MesoNAM Verification - Windows Internet Explorer


45th Weather Squadron MesoNAM Verification




45th Weather Squadron

MesoNAM Verification Tool V2.0, July 2010

Developed by NASA's Applied Meteorology Unit



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Help/About this Tool

Final Report

While this Help/About page provides an overview of this tool, it is highly recommended that users read the final report prior to using this tool. The final report, located [here](#), contains all of the details of the work conducted on this task leading up to the development of this tool.

Background

In order to have tangible evidence of model performance, the 45th Weather Squadron (45 WS) tasked the Applied Meteorology Unit (AMU) to conduct a detailed statistical analysis of model output compared to observed values. The model products are provided to the 45 WS by ACTA, Inc. and include hourly forecasts from 0 to 84 hours based on model initialization times of 00, 06, 12 and 18 UTC. The objective analysis compared the MesoNAM forecast winds, temperature and dew point to the observed values from the sensors in the KSC/CCAFS wind tower network shown in Table 1. The sensor heights required for this task are in the column labeled "Original Sensor Heights". Remaining sensors on Towers 002, 006, 108 and 110 were added for completeness and those sensor heights are shown in the column labeled "Additional Sensor Heights". Objective statistics will give the forecasters knowledge of the model's strength and weaknesses, which will result in improved forecasts for operations.

Tower Number	Supported Activity and Facility	Required Sensor Heights	Additional Sensor Heights
002	Delta II (LC-17)	6 ft, 54 ft, 90 ft	145 ft, 204 ft
006	Delta IV (LC-37)/Falcon 9 (LC-40)	54 ft	6 ft, 12 ft, 162 ft, 204 ft
108	Delta IV (LC-40)/Falcon 9 (LC-40)	54 ft	6 ft, 12 ft
110	Atlas V/Falcon 9 (LC-40)	54 ft, 162 ft, 204 ft	6 ft, 12 ft
041	Atlas V (LC-41)	230 ft	
393/394	Shuttle (LC-39A)	60 ft	
397/398	Shuttle (LC-39B)	60 ft	
511/512/513	Shuttle Landing Facility	6 ft, 30 ft	

The gridpoint forecast in the MesoNAM bulletin is identified as KXMR but the data is actually located at the point in Figure 1 which is southwest of KXMR and identified as "NAM". Although the model gridpoint is located over the Banana River, the model resolution is not fine enough to differentiate between water and land in the KSC/CCAFS vicinity, therefore the gridpoint is assumed to be over land.




Figure 25. The "Help/About" page from the GUI.

7. Summary and Conclusions

The AMU conducted an objective analysis of the MesoNAM forecasts compared to observed values from sensors at specified KSC/CCAFS wind towers by calculating the following statistics to verify the performance of the model:

- Bias (mean difference),
- Standard deviation of Bias,
- Root Mean Square Error (RMSE), and
- Hypothesis test for Bias = 0.

The 45 WS LWOs use the MesoNAM to support launch weather operations. However, the actual performance of the model at KSC and CCAFS had not been measured objectively. The analysis compared the MesoNAM forecast winds, temperature and dew point to the observed values from the sensors on wind towers. The data were stratified by tower sensor, month and onshore/offshore wind direction based on the orientation of the coastline to each tower's location. The model's performance statistics were then calculated for each wind tower based on sensor height and model initialization time. The period of record for the data used in this task was based on the operational start of the current MesoNAM in mid-August 2006 and so the task began with the first full month of data, September 2006, through May 2010.

The analysis of model performance indicated:

- The accuracy decreased as the forecast valid time from the model initialization increased,
- There was a diurnal signal in T with a cool bias during the late night and a warm bias during the afternoon,
- There was a diurnal signal in T_d with a low bias during the afternoon and a high bias during the late night, and
- The model parameters at each vertical level most closely matched the observed parameters at heights closest to those vertical levels.

The AMU developed a GUI that consists of a multi-level drop-down menu written in JavaScript embedded within the HTML code. This tool allows the LWO to easily and efficiently navigate among the charts and spreadsheet files containing the model performance statistics. The objective statistics give the LWOs knowledge of the model's strengths and weaknesses and the GUI allows quick access to the data which will result in improved forecasts for operations.

References

- Bauman, W. H., W. P. Roeder, R. A. Lafosse, D. W. Sharp, and F. J. Merceret, 2004: The Applied Meteorology Unit – Operational Contributions to Spaceport Canaveral. Preprints, 11th Conference on Aviation, Range, and Aerospace Meteorology, Amer. Meteor. Soc., Hyannis, MA, 4-8 October 2004, 24 pp.
- Insightful Corporation, 2007: S-PLUS[®] 8 for Windows[®] User's Guide, Insightful Corp., Seattle, WA, 584 pp.

List of Acronyms

45 WS	45th Weather Squadron	MesoNAM	12-km resolution NAM
AMU	Applied Meteorology Unit	NAM	North American Mesoscale
CCAFS	Cape Canaveral Air Force Station	MSE	Mean Square Error
GUI	Graphical User Interface	NM	Nautical Mile
HTML	Hyper-Text Markup Language	POR	Period of Record
KTTS	Shuttle Landing Facility 4-letter identifier	QC	Quality Control
KSC	Kennedy Space Center	RMSE	Root Mean Square Error
KXMR	CCAFS rawinsonde 4-letter identifier	WRF	Weather Research and Forecasting
LWO	Launch Weather Officer		

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